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Multiple orientations research on heat transfer performances of Ultra-Thin Loop Heat Pipes with different evaporator structures

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ABSTRACT

Two Ultra-Thin Loop Heat Pipe (ULHP) prototypes with parallelogram and trapezoid evaporator configurations were developed for battery thermal management system (BTMS). The dissimilarities between their heat transfer characteristics including the critical work angles, the start-up features, the thermal resistances and the flow instability were all explored and compared with experiments conducted under multi-orientations. The specific influences of these two evaporator configurations on the stable operation of ULHP have been fully acknowledged. The experiments results demonstrated that both the two ULHP prototypes displayed good performances with limited assistance from the gravity, meeting the demand of working under multiple orientations. Specially, the parallelogram configuration showed superior performance in resisting gravity by better suppressing the flow instability, the ULHP could not only start up under 15° inclination, but also the recession in heat transfer capability with placed angles was limited in 4%. Meanwhile, a reasonable mathematics model was established based on the steady operation state of ULHP, the predicted value fitted well with the experimental results.

1. Introduction

Recently, with the rapid development of electric vehicle, higher performance requirement of electric power battery has been put forward and draws attention, the corresponding battery thermal management system (BTMS) is getting urgently demanded. Alvani-Soltani pointed out that the uneven temperature distribution or temperature greatly change would lead to the early damage or thermal runaway of the battery, even cause serious safety problem [1]. The battery thermal safety problem is a big obstacle for the wide application and usage of electric vehicles [2]. So far, the available technology applied in battery thermal management includes the air cooling method [3–5], liquid cooling method [6] and phase change material method [7–9]. However, a common problem exists in all these mentioned technologies is the complex structures as well as the huge weight and volume, which not only increases the extra energy consuming, but also goes against the development requirement of automobile lighting. In the future, the required battery thermal management should be conveniently installed, lightweight in both weight and volume, and minimized in secondary energy consumption. Thus, *as a passive and effective heat transfer device, the heat pipe technology attracts more attention to be further applied in BTMS.*

Loop heat pipe (LHP) is a highly effective phase change heat transfer device linked by vapor line and liquid line. The heat transfer of LHP is realized by the phase change process of working fluid during circulating between the evaporator and condenser. A significant feature in structure of LHP is the separated vapor line and liquid line and the integration of the evaporator and the compensator, which determines the characters in heat transfer such as the small carrying resistance of steam, the quick start-up and multidirectional long distance heat transmission capability. With the fast development of electronic cooling, the micro flat loop heat pipe that can fit closely with the electronic components surface receives great attention [10–12]. However, the improvement of heat transfer capability of traditional LHP relies on the development of capillary core which requires not only the high capillary limitation but also the low flow resistance, yet the capillary core results in the heat leakage easily and increases the difficulty for LHP to start-up at low heat load [13–14]. Moreover, the capillary core is generally relatively heavy, Valery M. Kiseev [15] pointed out with experiments that the evaporator of LHP worked best with capillary core in 5–7 mm thickness. As one of the heat transfer enhancement technologies, micro channel receives widely attention. Taking advantage of the characteristic of micro channel, the capillary core structure was replaced by it in the evaporator, and combined with the feature of separated vapor/liquid line of LHP, the Ultra-thin Loop Heat Pipe (ULHP) was developed, the design details can been referred in paper [16], yet its performance and application needed

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Nomenclature

a_0	the volume fraction of liquid at the entrance of evaporator
a_1	the volume fraction of liquid at the exit of evaporator
b	the number of tests
c	the number of variables
d_1	the equivalent diameter of single micro channel, m
d_2	the inner diameter of loop heat pipe, m
h	the height of the drawdown, m
i	the sequence number of tests
j	the sequence number of variables
k	the coverage factor
m	the evaporation rate, kg/s
n	the total number of micro channels
u_1	the speed of working fluid in the loop pipe, m/s
u_2	the speed of working fluid in the micro channel, m/s
β	the proportion of evaporation heat and total input heat
ε_v	the frictional resistant coefficient
ρ_h	the density of high temperature vapor, kg/m^3
ρ_v	the density of low temperature vapor, kg/m^3
ρ_l	the density of liquid, kg/m^3
σ	the surface tension coefficient, N/m
A_1	the cross section area of loop pipe, m^2
A_2	the cross section area of single micro channel, m^2
Cp	the specific heat at constant pressure, J/kg·K^{-1}
FR	the filling ratio of the ULHP
$H_{f.g}$	the latent heat of phase change, J/kg
L_e	the length of the evaporator, m
L_c	the length of the condenser, m
$L_{v.l}$	the length of the vapor line, m
$L_{l.l}$	the length of the liquid line, m
ΔP_f	the frictional resistance of loop pipe, N
$\Delta P'_f$	the frictional resistance of micro channel, N
ΔP_g	the pressure load of gravity, N
$\Delta P'_g$	the inverse gravity loss of upstream, N
ΔP_s	the saturated pressure, N
$\Delta P_{capillary}$	the resistance of capillary hysteresis, N
Q_{in}	the total input heat load, W
R	the thermal resistance, K/W
T_s	the saturated temperature, K
$T_{evap.}$	the average temperature of evaporator, $T_{evap.} = (T_1 + T_2 + T_3 + T_4)/4$, K
$T_{cond.}$	the average temperature of condenser, $T_{cond.} = (T_6 + T_7)/2$, K
ΔT_e	the temperature rise of evaporator, K
U	the uncertainty error
X	the Type B test error

to be discussed for further practical application in various operating conditions of BTMS. As to the structure, ULHP resembles Two-phase Loop Thermosyphon [17–20] which however could not work under multiple dimensions as LHP and the thermal capability has been only discussed in vertical orientation so far. Hence, the research of ULHP's performance under various inclinations plays a significant role in guiding the further practical application of ULHP, especially in BTMS.

As the structure inside the evaporator is micro channels instead of capillary core structure, which though brought about the enhancement in heat transfer, but triggered the flow instability and the fluctuation of temperature/pressure. The fluctuation of temperature/pressure and the flow instability [21,22] were always caused by the fast transformation of two-phase flow limited by the micro-channel size. The recession in heat transfer ability usually including the Pre-Critical Heat Flux (PCHF) and the local dry-out, sharp rising of the surface temperature of devices and violent oscillation of pressure would be observed. Especially, when the placed angles decreased and the assistance of the gravity became weaker, the flow instability became more severe, the practical application of the ULHP would be limited.

Aims to make sure that the ULHP can work under multiple orientations, the micro channels inside the evaporator brought not only the enhancement in heat transfer, but also the flow instability and the fluctuation of temperature as well as the pressure, which might result in the recession in heat transfer ability, especially when the flow instability became more severe caused by the various orientations, the practical application of the ULHP would be limited. Therefore, in order to improve the circulation efficiency of the working fluid inside the ULHP by solving the flow instability, two prototypes of ULHPs with a parallelogram and a trapezoid evaporator configuration were developed, the difference between their heat transfer capabilities and the effectivities in suppressing flow instability were compared under various angels, the operation characteristics of these two ULHP in antigravity conditions were well understood, and the effectiveness of ultra-thinning and lighting the loop heat pipe was verified.

Aims to make sure that the ULHP can work under multiple orientations and be adapted to the complex working conditions in BTMS, It is necessary and essential to examine the performance consistency and the operation stability for both the developed prototypes of ULHPs (with parallelogram/trapezoid configuration) under multi-orientation conditions. With experiments, the operation characteristics of these two ULHP under multiple orientations were well understood, and the effectiveness of ultra-thinning and lighting the loop heat pipe was verified. The exact influences of the configurations were clearly identified.

1. Experiment system

1.1. Designed samples

The ULHP we studied was shown in Fig. 1. The evaporator was a flat plate with micro-channels inside it. The copper made ULHP can be divided into four parts—the evaporator, the condenser, the vapor line and the liquid line, the values were all listed in Table 1. The length of the entrance section and the length of the vapor/liquid lines were specifically explored and determined with series of experiments. Relevant results and conclusions can be referred to paper [23]. The evaporator of the ULHP was made of two pieces of copper plate. One plate was a 0.5 mm thick smooth plate using as the cover, the other one was 1 mm thick and used as the base board. The groove structure was milled in the base board. 25 rectangle grooves with 3 mm in width and 0.6 mm in depth placed in parallel. For Sample A, the configuration of the channels was parallelogram, the upper and lower edge paralleled to the lower right, the angle between the upper edge and the horizontal is defined as θ_1, θ_1 is measured as 3.434°. As to Sample B, the distribution of the channels is changed into the trapezoid. The upper edge keeps the same incline as that of Sample A whereas the lower edge inclines symmetrically and forms an isosceles trapezoid shape. The angle between the lower edge and the horizontal here is θ_2, which is also 3.434°. Due to the special channel arrangement, a larger